Measurements of He I λ5876 Recombination Line Radiation from the Diffuse, Warm Ionized Medium in Irregular Galaxies[1]

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ABSTRACT

We present longslit optical spectroscopy of three high surface brightness Magellanic irregular galaxies. This paper draws attention to our detection of He I λ5876 line emission from the ionized gas outside the HII regions, or the warm ionized phase of the interstellar medium. We measure a mean reddening-corrected intensity ratio of He I λ5876 / H$\alpha \approx 0.041$ independent of spatial location. This ratio is much higher than that measured in the diffuse, warm ionized interstellar medium of the Milky Way (Reynolds & Tufte 1995).

The high value of He I λ5876 / Hα implies the helium ionization fraction is approximately equal to the hydrogen ionization fraction in the diffuse ionized gas (DIG). If the DIG is powered by young stars, then stars hotter than 40,000 K must contribute to the Lyman continuum radiation reaching the DIG. Since optical and ultraviolet spectra confirm the presence of such massive stars in these galaxies, stellar photoionization remains the most likely power source. The contrast with the low helium ionization in the Galactic DIG, however, is intriguing and provides strong evidence that the physical state of the DIG, not just its presence, varies among galaxies.

Subject headings: ISM: structure – galaxies: individual NGC 1569, NGC 4214, NGC 4449 – galaxies: irregular – galaxies: ISM

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1. Introduction

Warm, diffuse ionized gas (DIG) comprises a significant fraction of the mass and volume of the interstellar medium (ISM) in galaxies. In the Milky Way, this component is sometimes referred to as the Reynolds Layer and has a scale height ~ 1 kpc (Reynolds 1991). Galactic O and B stars supply enough power to keep it ionized (Reynolds 1984), and the only conundrum had been how the Lyman continuum radiation from O and B stars, with scale height ~ 100 pc, can reach the DIG. The close correlation between the presence of extended, diffuse ionized gas in other galaxies and various tracers of massive star formation seemed to place the OB-star photoionization hypothesis on relatively firm ground (Hunter & Gallagher 1990; Dettmar 1992; Rand 1996).

The massive-star photoionization picture has been challenged, however, by new measurements of the He ionization fraction in the Galactic DIG. First, a search for He I $\lambda5876$ recombination line emission from the local DIG set an upper limit on the He I $\lambda5876$ / Hα intensity ratio of 0.011 (Reynolds & Tufte 1995). For a He/H abundance ratio of 1:10 by number in the DIG, the implied relative ionization fraction is $\chi(\mathrm{He})/\chi(\mathrm{H}) \equiv (n(\mathrm{He}^+)/n(\mathrm{He}))\ /\ (n(\mathrm{H}^+)/n(\mathrm{H})) \lesssim 0.25$. This high neutral fraction of He implies that the interstellar radiation field is softer than that expected from the Galactic O star population in the solar neighborhood (Reynolds & Tufte 1984). Further work has shown that this curiosity is not confined to the solar neighborhood. Heiles et al. (1996) observed hundreds of positions toward the Galactic center at ~ 1.5 GHz. The relative strengths of the H and He radio recombination lines from the quasi-vertical filaments of ionized gas known as "worms" indicate a relative ionization fraction $\chi(\mathrm{He})/\chi(\mathrm{H}) \lesssim 0.13$ there, which implies that stars more massive than about 39 $M_\odot$ must not contribute to the ionizing continuum (Heiles et al. 1996). To meet the measured ionization rate in the Galaxy, however, the global star formation rate would need to be significantly higher than previously estimated (Heiles et al. 1996).

Nearby galaxies provide an opportunity to examine the relationship between the properties of the DIG and the stellar content of a galaxy. Among normal galaxies, Magellanic irregular galaxies have the most intense star formation in terms of both the number of HII regions per unit luminosity and the ionizing luminosity of the brightest HII region (Kennicutt, Edgar, & Hodge 1989). To investigate the ionization state of He in the warm ionized phase of the ISM of such galaxies, we selected three irregular galaxies with copious amounts of diffuse and filamentary Hα emission from a larger sample of dwarf galaxies (Martin 1996b). In this paper, we report measurements of the He I $\lambda5876$ line emission in the DIG from longslit spectra. A more detailed discussion of the emission-line spectra and their implications for the excitation of the DIG can be found in Martin (1997a).

2. Measurements of He I λ5876 Line Emission

2.1. The Galaxies

The galaxies NGC 4214, NGC 1569, and NGC 4449 were selected for their star formation activity, proximity, and prominence of ionized gas beyond the HII regions. They are gas-rich and have absolute blue luminosities between those of the Small Magellanic Cloud and Large Magellanic Cloud. Table 1 compares some relevant properties of the observed galaxies to the Milky Way. Their current rates of massive star formation, 0.25 and 0.50 $M_{\odot}$ yr^{-1}, are only ~ 5 times lower than that in the Milky Way but, unlike our Galaxy, are equal to or a few times larger than the past average rate of star formation in each galaxy (Kennicutt 1983; Kennicutt, Tamblyn, & Congdon 1994). Spatial and temporal fluctuations in the star formation rate have clearly occurred. For example, the northern region of NGC 4449 is younger than the main bar (e.g. Hill et al. 1994); and NGC 1569 is emerging from a major burst of star formation (Israel & de Bruyn 1988; Waller 1991; Heckman et al. 1995). Their lower oxygen abundance, O/H $\gtrsim$ 0.20 (O/H)$_{\odot}$, is also consistent with a much lower total amount of star formation in the past (Martin 1997a).

2.2. Observations and Reductions

We obtained longslit spectra at 11 positions across these galaxies at the Multiple Mirror Telescope during the period February 1994 to March 1995. The Blue Channel spectrograph was used with a 500 gpm grating, a Loral 3k $\times$ 1k CCD detector, and a $1''$ by $3'$ slit. This setup produced wavelength coverage from 3700 – 6800 Å and a spectral resolution of 4 - 5 Å at Hα . Slit positions were chosen in advance to sample both HII regions and extended, diffuse emission and were required to be close to the parallactic angle at the time of observation. Their exact locations are illustrated in Martin (1997a), where additional details about the observations and reductions can be found. The spectra reach a surface brightness $\sim 2.5 \times 10^{-17}$ ergs s^{-1} cm^{-2} arcsec^{-2}, which corresponds to an emission measure of 14 at $T_e = 10^4$ K.

The He I λ5876 line is clearly visible along a substantial length of the slit in the raw data. We divided this region into $3''$ apertures and extracted a series of one-dimensional spectra from the sky-subtracted and continuum-subtracted frames as described by Martin (1997a). Fortunately, the recessional velocities of these galaxies are less than 300 km s^{-1} , so the line is cleanly separated from the bright night sky emission at Na I $\lambda\lambda$ 5890,96. Our continuum template does not include line emission, so stellar absorption/emission lines are present in the continuum-subtracted frames. The correction to the nebular He I λ5876

emission will only be significant where the emission line is weak relative to the continuum, and very little continuum emission underlies most of the low surface brightness DIG in our spectra. Measurements from our spectra of the HII regions, however, do show a slight trend for the He I λ5876 / Hα ratio to decrease as the emission-line equivalent width decreases. The slope of this relation places an upper limit of 0.3 Å on the equivalent width of the underlying He I λ 5876 absorption there.

The He I λ5876, Hα , and Hβ fluxes were measured from these spectra using the 'splot' task in IRAF. The He I λ5876 / Hα ratio was corrected for reddening using the extinction curve of Miller and Matthews (1972) and the logarithmic extinction at Hβ , c(Hβ). We derived c(Hβ) from the Balmer decrement assuming a constant underlying stellar absorption equivalent width of 2 Å $\pm$ 2 Å and an electron temperature of $15,000$ K. We found little variation of c(Hβ) with position along the slit, so the mean value was adopted at each position angle. An uncertainty, δc(Hβ) in Table 1, was assigned based on the variation in c(Hβ) along the slit or the formal error, whichever was larger. This term dominates the error estimates of the He I λ5876 / Hα intensity ratio. Only a portion of the data were obtained under photometric conditions, but the relative flux calibration for all observations is good to $\sim$ 2%, based on observations of multiple standard stars (Massey et al. 1988).

2.3. Results

Figure 1a shows the reddening-corrected ratio of the He I λ5876 to Hα emission-line intensity as a function of Hα surface brightness along the 11 slit positions. The Hα surface brightness is closely correlated with the angular distance from the nearest giant HII region along our slit positions (see Figure 2) and can therefore represent the relative distance of the aperture from the ionizing cluster. The average He I λ5876 / Hα intensity ratio is 0.041, the lowest value is 0.028, and the highest value is 0.058. Comparison with panel b shows only NGC 1569 and position 3 in NGC 4449 (PA = 137.2°) have large corrections for reddening. Across each galaxy, we find no systematic variation in He I λ5876 / Hα despite a decline in Hα surface brightness by a factor of $\sim$ 100.

The gradients in other diagnostic line ratios measured from the same spectra emphasize the remarkable uniformity of He I λ5876 / Hα. Figure 2 demonstrates the contrast along position 2 in NGC 1569. Across the region where He I λ5876 / Hα is measured, the [SII]$\lambda\lambda$6717, 31 / Hα , [NII] λ6583 / Hα , and [OI]λ6300 / Hα ratios increase by factors of a few, while [OIII]λ5007 / Hβ decreases by a similar factor. This spectral change is typical of the DIG in low metallicity galaxies (Martin 1997a). Martin (1997a) studied these

spectral changes using photoionization models and found the gradients in the line ratios primarily reflect a gradient in the relative density of ionizing photons to gas. The ionization parameter is inferred to fall by a factor $\gtrsim 10$ over the region where we have measured a constant He I $\lambda5876$ / Hα ratio (Table 2).

Under normal conditions, the relative intensity of He I $\lambda5876$ / Hα can be predicted from the effective recombination coefficients of He and H. At $T = 10^4$ K and $n = 100$ cm^{-3}, the recombination coefficients for He and H from Brocklehurst (1972) and Hummer & Storey (1987), respectively, yield an emissivity ratio

$$\frac{E_{5876}}{E_{H\alpha}} = 0.470 \frac{\mathrm{He}}{\mathrm{H}} \frac{\chi(\mathrm{He})}{\chi(\mathrm{H})}, \tag{1}$$

where He/H is the abundance ratio by number. (The revised emissivities of Smits (1996) would raise the coefficient in equation 1 by 0.004, while raising the temperature to 1.2×10^4 K would lower it by 0.004). Assuming that the abundance ratio of He / H by number is $\lesssim 0.1$ and comparing the measured intensity ratios with equation 1, we see that $\chi(\mathrm{He})/\chi(\mathrm{H}) \approx 1$.

If we adopt $\chi(\mathrm{He})/\chi(\mathrm{H}) = 1$, then the mean ionic abundance of He$^+$ relative to H$^+$ is $\frac{\mathrm{He}^+}{\mathrm{H}^+} \equiv \bar{y}^+ = 0.085$, which is consistent with the He/H ratio predicted by the He vs O regression relation of Pagel et al. (1992) for the oxygen abundance, $\log(\mathrm{O/H}) = -3.69 \pm 0.07$, in NGC 4449. The slightly lower O/H ratios in Table 1 for NGC 1569 and NGC 4214 are not unusual for an abundance ratio He/H ≈ 0.085. For example, within the O/H range of our three irregular galaxies, Table 15 of Pagel et al. (1992) contains HII regions with y^+ varying from 0.081 to 0.090. Also, Kobulnicky & Skillman (1996) find variations in O/H within NGC 4214 as large as $\sim 45\%$ whereas He$^+$/H$^+$ changes by only $\sim 6\%$ among the same regions.

3. Discussion: The Source of Ionizing Photons

Our spectra also show evidence for emission from gas excited by 60 – 100 km s^{-1} shocks (Martin 1997a). These results are discussed in depth in a second paper, and we comment here only on the sensitivity of He I $\lambda5876$ / Hα to shock velocity. In the models of Shull & McKee (1979), He I λ 5876 emission is negligible until shock speeds reach 80 km s^{-1} ; even then, the He I $\lambda5876$ / Hα intensity ratio is only 0.005. Increasing the shock speed to 100 km s^{-1} , however, raises He I $\lambda5876$ / Hα to 0.047. It is possible then that shocks may contribute to the high values in Figure 1. However, we suspect the correction is not large because (1) shock-excited gas typically contributes $\lesssim 20 - 30\%$ of the emission, and (2)

while the relative contribution from shocked gas grows with distance from the star forming regions, the He I λ5876 / Hα ratio exhibits no systematic variation (Figure 1). The relative amounts of He and H ionization in the DIG are therefore a measure of the hardness of the Lyman continuum radiation ionizing the DIG.

3.1. The Lyman Continuum

Figure 3 illustrates the dependence of the He I λ5876 / Hα intensity ratio of an HII region on the stellar luminosity of He-ionizing photons relative to H-ionizing photons, Q(He)/Q(H). The ratio He I λ5876 / Hα increases linearly with Q(He)/ Q(H) until H begins to compete for $h\nu > 24.6$ eV photons and then saturates at a constant value when the volume-averaged $\chi(He) \approx \chi(H) \approx 1$ (Osterbrock 1989). In Figure 3, the arrow illustrates the analytic relation for the linear rise; and the turnover is illustrated by the line ratios of the model nebula ionized by stars with Q(He)/Q(H) $\approx$ He/H. Since the mean He I λ5876 / Hα $= 0.041$ in these irregular galaxies, we see from Figure 3 that the Lyman continuum must have Q(He)/Q(H) greater than 0.12; and this mean intersects the relation for the He/H = 0.85 models at Q(He)/Q(H) $\approx$ 0.25. The He I λ5876 / Hα intensity ratio is, however, not very sensitive to the spectral hardness at temperatures hotter than $T_{eff} = 40,000$ K.

The equivalent stellar mass depends on the stellar metallicity, the stellar atmospheres chosen, and the adopted grid of evolutionary models. To illustrate the sensitivity to these assumptions, four mass scales are shown at the top of Figure 3. For example, using the most recent atmospheres from Schaerer et al. (1996) and the evolutionary models of Schaller et al. (1992) as parameterized by Vacca et al. (1996), the spectrum is harder than that of a ~ 30 M$_\odot$ solar metallicity star (scale c). If we use the same models as Heiles et al. (1996) for a direct comparison with their analysis of the Milky Way DIG, the minimum mass star that has a spectral hardness consistent with the He-ionization of the DIG in the irregular galaxies is ≈ 44 M$_\odot$.

Of course many stars contribute to the ionization of the DIG, and the Q(He)/Q(H) ratio of the ensemble will be less than that emerging from the most massive star. The 0.25 Z$_\odot$ evolutionary synthesis models of Leitherer & Heckman (1995), for example, predict a spectral hardness Q(He) / Q(H) = 0.23 and Q(He)/Q(H) = 0.07 from stellar populations continuously forming stars with a Salpeter initial mass function (IMF) and upper mass limits of $m_u = 100$ M$_\odot$ and 30 M$_\odot$ respectively. The ratio can be considerably higher, Q(He) / Q(H) = 0.32, if the burst is less than a few Myr old. Hence, 30 M$_\odot$ is only a lower limit on the upper mass cut-off of the stellar population ionizing the DIG.

3.1.1. Direct Evidence for Massive Stars

Optical and ultraviolet spectra provide direct evidence for massive stars in all three galaxies. Several HII regions in NGC 4214 show strong, broad He II λ4686 and C IV $\lambda\lambda$ 5808 emission lines from WN and WC stars (Sargent & Filippenko 1991). Our spectra also reveal both of these features in several HII regions in NGC 4449 as well as broad λ4686 in NGC 1569 (cf. Drissen, Roy, & Moffat 1991; Gonzalez-Delgado et al. 1997). These Wolf-Rayet stars are thought to be the short-lived descendants of the most massive O stars ($M \geq 35$ M$_\odot$) (Conti et al. 1983; Humphreys, Nichols, & Massey 1985). Spectral synthesis modeling of the ultraviolet continuum from the most prominent cluster in NGC 4214 suggests several hundred O stars are present in addition to the ~ 30 Wolf-Rayet stars (Leitherer et al. 1996). Hence, the hard interstellar Lyman continuum in these irregular galaxies is not unexpected. It is, rather, the contrast between the spectral energy distribution of the photons ionizing the DIG in irregular galaxies and the Milky Way that is of interest.

3.2. The Morphology Problem

The morphology problem in the Galaxy, again, is how the ionizing photons from O and B stars, scale height ~ 100 pc, can reach the DIG when their absorption mean free path is only $0.5(0.1 \text{ cm}^{-3}/n_H)$ pc at 1 Rydberg (e.g. Dove & Shull 1994; Miller & Cox 1993). In irregular galaxies, the DIG also extends over a kiloparsec from the main star forming regions. And, in both environments, spectra of DIG regions ~ 100 times fainter than the discrete HII regions (Reynolds 1991; Reynolds & Tufte 1995), indicate the ionization parameter is very low (Dömgorgen & Mathis 1994); Martin 1997a). These conditions are consistent with a distant source of ionizing photons. However, the spectroscopic signature of gas photoionized by a distant association is nearly indistinguishable from that of a dilute HII region; and it is worthwhile to re-examine the possibility that the DIG in irregular galaxies might be ionized locally and the radiation transport problem avoided.

About 80% of the ultraviolet light from starburst regions is believed to come from massive stars between and beyond the young clusters (Meurer et al. 1995). However, since most studies of the individual massive stars in these galaxies have focused on star clusters, it is not clear at present how far from the clusters the young field population might extend (cf. Gallagher et al. 1996). In extreme environments, such as the outflow extending several kpc above the disk of NGC 1569 (Heckman et al. 1995), it seems highly unlikely that the DIG is ionized by nearby stars. In addition to the difficulties of forming stars in the tenuous outflow, the dramatic increase in Hα equivalent width with radius (cf. Figure 5a Waller

1991) is most naturally explained by photons escaping the starburst region and/or shock excitation. However, the situation is much less clear a few hundred parsecs to 1.5 kpc away from the clusters – the type of environment well-sampled by our spectra; and it is here that we consider whether the DIG could be comprised solely of low surface brightness HII regions excited by a young field population

3.2.1. Is Local Ionization Consistent with the Spectral Gradient?

Such a question is hard to answer definitively without observing the presence/absence of an extended population of hot stars. However, some insight can be obtained by investigating whether such an assertion is compatible with the observed spectral gradient. For the purpose of illustration, we take the viewpoint that all the HII regions are ionization bounded, and that the radial gradients in Hα surface brightness (Σ) and ionization parameter (U) result from changes in the HII region population. The simplest possible geometry for the HII regions surrounding an isolated star or cluster is a homogeneous Strömgren sphere a fraction ϵ of which is filled with gas clouds of density n. The nebular ionization parameter will scale as

$$U \propto Q^{1/3} n^{1/3} \epsilon^{2/3}, \tag{2}$$

where Q is the ionizing luminosity of the star or cluster; and the average Hα surface brightness of the nebulae will scale as

$$\Sigma \propto Q^{1/3} n^{4/3} \epsilon^{2/3}. \tag{3}$$

These scaling relations are reasonably robust with respect to the local nebular geometry. For example, if the circumstellar medium surrounding each massive star has been swept into a thin shell of thickness $\triangle R = (4/3\pi R^3 n_0)/(4\pi R^2 4 n_0) = 1/12R$, the same scaling arguments would continue to hold under the assumption that the nebulae remain ionization bounded. The absolute surface brightness and ionization parameter of the shell and filled sphere models would of course differ, but they scale in the same manner with Q, n, and ϵ.

From equations 2 and 3, we see that a large-scale gradient in the ambient gas density is insufficient by itself to explain the spectral gradient. Using equation 2, a smooth change in gas density of a factor of 10^3 between the giant HII regions and the DIG could produce the observed drop, a factor of ten, in ionization parameter. Equation 3 predicts the surface brightness of the low density nebulae would, however, be a factor of 10^4 times fainter than the giant HII regions – a much greater contrast than observed.

In principle, a decrease in the luminosity of the star clusters with galactic radius could produce a gradient in the nebular spectrum and alleviate the need to transport ionizing

photons large distances. The three order of magnitude drop in Q required to reduce the ionization parameter by a factor of ten would be similar to the difference in ionizing luminosity between a giant HII region and a single hot star, so individual, isolated stars would be ionizing the lowest surface brightness DIG. Although the accompanying reduction in Hα surface brightness is only a factor of ten, the surface brightness could be decreased further to the observed factor of 100 by a mild density gradient in the ambient medium without decreasing the ionization parameter much beyond the measured range. Ionization of the DIG by a population of field O and B stars cannot, therefore, be ruled out.

Such an interpretation, however, implies a very smooth radial change in the luminosity of the ionizing star clusters to generate the smoothness of the spectral gradient. Until such spatial changes in the cluster luminosity function are observed, we remain highly skeptical of this explanation and continue to favor a scenario where the DIG is powered mainly by the major star forming regions in these irregular galaxies. The photons ionizing the DIG are most likely leaking out of the giant HII regions and traveling very large distances before being absorbed. Additional support for this leakage is provided by Leitherer et al. (1996) who resolved the central starburst in NGC 4214 and demonstrated that the HII region around it is density bounded.

3.3. Speculation on the Variations among Galaxies

Since the He ionization fraction in the DIG of these irregular galaxies is so much higher than in the Milky Way, one might question whether the extra-HII region Hα emission in Magellanic irregular galaxies is a good analogy to the Reynolds Layer in the Milky Way? Many properties of the widespread ionized gas in these galaxies are compared to those in the Mikly Way DIG in Table 2. The differences are not limited to the He ionization fraction. The surface brightness of the regions studied spectroscopically in the irregular galaxies is about five times brighter than even the DIG in the Galactic plane studied by Reynolds. In addition to diffuse (i.e. unresolved?) emission, the DIG in the irregular galaxies contains a highly structured component of shells, arcs, and radial filaments, sometimes referred to as "interstellar froth" (Hunter & Gallagher 1990). Despite these differences, we believe the analogy is interesting because the DIG in irregular galaxies seems to share the morphology problem with the Reynolds Layer.

The He I $\lambda5876$ / Hα spectral differences among different types of galaxies demonstrate that the physical conditions within the warm-ionized phase of the ISM vary. The surprisingly low He I $\lambda5876$ / Hα ratio is not limited to the Milky Way. Rand (1996) recently reported He I $\lambda5876$ / Hα ≈ 0.034 about 1.5 kpc above the plane of NGC 891, an

edge-on Sbc galaxy with a prominent DIG component. The inferred He ionization, about 70%, is intermediate to irregular galaxies and the Milky Way. The high [NII] λ6583 / Hα in NGC 891 relative to the Milky Way, however, still seems to require a harder spectrum than the He I λ5876 / Hα ratio (Rand 1996).

It remains unclear why the He ionization fraction in the DIG of NGC 891 and the Milky Way is lower than expected. Compared to the irregular galaxies, the dust content and metallicity are higher; but the ionizing luminosity of the largest star-forming complexes tends to be smaller than in the irregular galaxies. Accounting for this absorption will, however, harden the Lyman continuum thereby magnifying the discrepancy (Sokolowski 1994; Shields & Kennicutt 1995). For the Milky Way, Dove & Shull (1994) have demonstrated how the hierarchical network of Stromgren spheres created by the distributions of hot stars and gas increases the probability of an ionizing photon reaching the DIG. It is unclear whether a higher escape probability from the vantage point of large clusters in irregulars could make the escaping Lyman continuum relatively harder. We are reluctant to suggest systematic differences in the IMF since Massey (1997 and references therein) measure similar IMFs in the Magellanic Clouds and Milky Way; however, as more data become available, the possibility of systematic variations in the IMF may need to be re-considered.

A final, but important, consideration for reconciling the interstellar Lyman continua is the accuracy of the stellar atmosphere calculations. One of the two massive stars observed with EUVE, ϵ CMa, is a case in point. The Lyman and He I continua of this B2 II star are $\gtrsim$ 30 times higher than expected making it the dominant source of ionizing photons within a few hundred parsecs of the sun (Cassinelli et al. 1995). More reliable predictions of the ionizing flux from stars this cool are needed to determine whether B stars can ionize much of the Galactic DIG. New model atmospheres for O stars including the velocity gradient in the stellar wind predict an increase in the He II continuum by several orders of magnitude (Schaerer & de Koter 1996), and similar effects are expected in the He I and Lyman continua of B stars (Najarro et al. 1996). Since the objection to ionizing the DIG in the Milky Way with late O and early B stars is the high total star formation rate implied (Heiles et al. 1996), we explored the effect of the new model atmospheres of Schaerer & de Koter (1996) on the required star formation rate. For the same cutoff in upper mass as that used by Heiles et al. (1996), the new model atmospheres predict a lower star formation rate because the luminosity of hydrogen ionizing photons from stars with initial masses between 16 $M_\odot$ and 45 $M_\odot$ is increased. However, the ionizing continua are also harder, and the mass of the most massive star that can contribute to the ionization of the DIG is reduced from 39 $M_\odot$ to 25 $M_\odot$(see Figure 3). With this revised upper mass limit on the ionizing population of stars, the implied galactic star formation rate is twice that derived by Heiles et al. (1996) making the discrepancy with the measured star formation rate in the Galaxy

(e.g. McKee 1989) even larger

3.4. A Consistent Picture in Irregular Galaxies

We measure a mean He I λ5876 / Hα $\approx$ 0.040, 0.042, and 0.043 across NGC 1569, NGC 4214, NGC 4449, respectively, and find no evidence for a systematic variation in He I λ5876 / Hα with either Hα surface brightness or distance from the nearest giant HII region. This high relative ionization fraction requires an ionizing continuum at least as hard as that supplied by a 30 $M_{\odot}$ star, which is completely consistent with the expected hardness of the radiation from the young starburst regions in these galaxies. Although the transport of these photons over a kiloparsec to the DIG is not well-understood, it seems plausible that the plethora of expanding supershells of gas in these irregular galaxies (Hunter & Gallagher 1990; Hunter & Gallagher 1996; Martin 1996) creates a rather porous ISM which allows a fraction of the ionizing photons to travel large distances before absorption.

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Table 1: Properties of the Galaxies

Galaxy	NGC 1569	NGC 4214	NGC 4449	Milky Way
d (Mpc)[a]	2.2	3.6	3.6	$\cdots$
c(Hβ)[b]	0.85 ± 0.3	0.16 ± 0.1	0.29 ± 0.3	$\cdots$
Γ (s^{-1})[c]	3.9e52	2.1e52	4.5e52	$\gtrsim$ 1.4e53
b[d]	$\gtrsim 1$	$\gtrsim 1$	$\gtrsim 1$	≤ 1
log(O/H)[e]	-3.78 ± 0.07	-3.78 ± 0.07	-3.69 ± 0.07	-3.07
$M_{\rm HI}$ ($M_\odot$)[f]	8.4e7	1.1e8	2.4e9	4.8e9
Type[g]	IBm	IAB(s)m	IBm	$\cdots$

[a] Adopted distance (Martin 1996).

[b] Logarithmic extinction at Hβ (see text).

[c] Recombination rates calculated from the Hα fluxes of Kennicutt & Kent (1983) assuming an electron temperature of 10^4 K and the extinction in row 2. The Galactic rate is discussed by Heiles et al. (1996).

[d] Stellar birthrate parameter, the ratio of the current star formation rate to the past average rate (Kennicutt 1983; Kennicutt et al. 1994).

[e] Oxygen abundances for irregular galaxies from Martin (1997a); Galactic value from Grevesse and Anders (1989).

[f] Mass of neutral hydrogen from Reakes (1980), Hunter, Gallagher, & Rautenkranz (1982), Hunter & Gallagher (1986), and Kulkarni & Heiles (1987).

[g] Third Reference Catalog of Bright Galaxies

Table 2: The DIG in Different Types of Galaxies

Property	Milky Way	NGC 1569	NGC 4449	NGC 4214
He I λ5876 / Hα^{a}	$\cdots$	0.040	0.043	0.042
He I λ5876 / Hα^{b}	$\lesssim$0.011	0.032	0.039	0.040
χ(He)/χ(H) ^{c}	$\lesssim$ 0.23	$\sim$ 1	$\sim$ 1	$\sim$ 1
	$<$ 0.13			
$\Sigma_{\mathrm{H}\alpha}^{\mathrm{DIG}}$ ^{d}(R)	1 - 10	100	50	50
$\Sigma_{\mathrm{H}\alpha}^{\mathrm{HII}}$ (R)	10 - 500	10,000	4,500	4,500
$\log U$ (DIG)^{e}	$\lesssim -$ 4.1	-3.9	-4.3	-3.9
$\log U$ (HII)	$\cdots$	-2.24	-3.2	-2.9
Distance^{f}	$\approx$ 1000	950	1900	1200
		(400)	(1000)	(800)
Morphology^{g}	Diffuse	Diffuse + Filaments + Wind	Diffuse + Filaments	Diffuse + Filaments
M_u (M$_{\odot}$)^{h}	$\leq$ 39	$>$ 30	$>$ 30	$>$ 30

Notes – (a) Reddening corrected emission-line ratio. (b) Reddened line-ratio. Local value from Reynolds & Tufte (1995). (c) Relative ionization fraction. Galactic values from Reynolds & Tufte (1995) and Heiles et al. (1996). (d) The Hα surface brightness of the DIG compared to that of HII regions in the Im's and discrete sources in the Galactic plane (Reynolds 1983, 1984). One Rayleigh (R) is 10^6 photons s^{-1} cm^{-2} per 4π sr.
(e) Logarithm of ionization parameter, U, defined in terms of the ratio of ionizing photons to matter at the Strömgren radius, R_S, in the absence of absorption such that $U \equiv \frac{Q}{4\pi R_S^2 nc}$ (Martin 1997a; Domgörgen & Mathis 1994). (f) Projected distance from giant HII regions to the most extended Hα emission in our images and, in parentheses, to the boundary of our He I measurements. Estimated scale height of Galactic diffuse, ionized gas (Reynolds 1991). (g) Morphology of extra-HII region ionized gas. (h) Upper-mass limits on present day mass function of stars contributing to the ionization of the DIG (this paper and Heiles et al. 1996).

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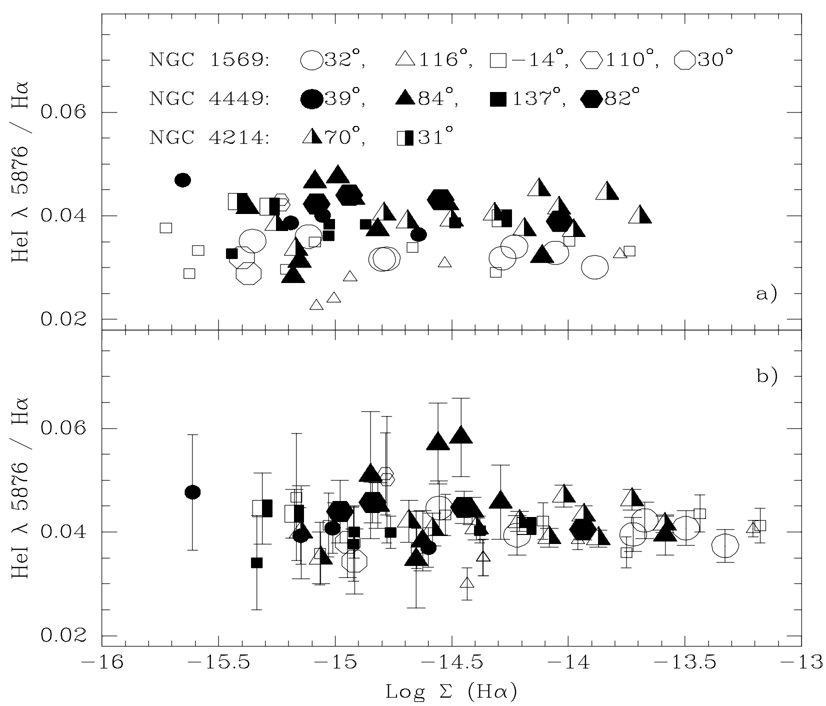

Fig. 1.— Dependence of the He I $\lambda 5876$ / Hα intensity ratio on Hα surface brightness: (a) without corrections for reddening, and (b) with the de-reddened line ratios and surface brightnesses. The surface brightness at the positions represented by large symbols is in units of ergs s^{-1} cm^{-2} $arcsec^{-2}$. The small symbols denote non-photometric data and could be misplaced by as much as ± 0.5 dex in surface brightness.

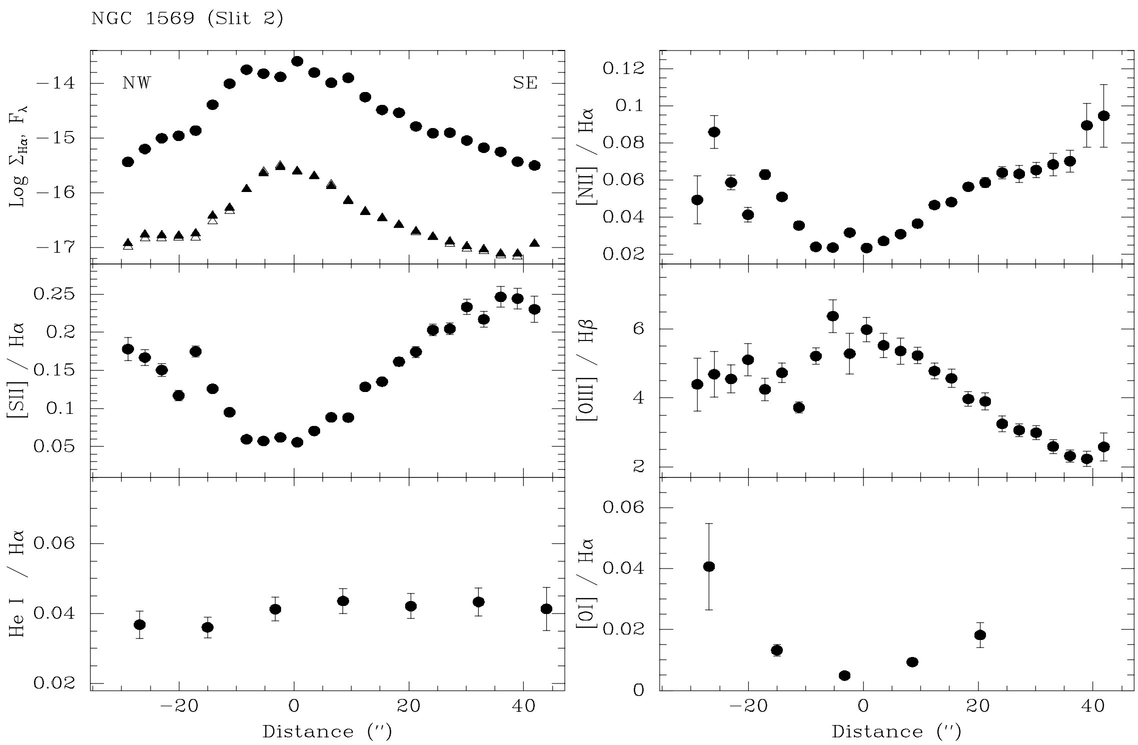

Fig. 2.— The changing emission-line spectrum across NGC 1569, PA = 32.4°. *Top Left:* Hα and continuum surface brightness versus separation from the brightest HII region along the slit. Counterclockwise from top left, the emission-line ratios are: [SII]$\lambda\lambda$6717, 31 / Hα ; He I λ5876 / Hα; [NII] λ6583 / Hα ; [OIII]λ5007 / Hβ ; and [OI]λ6300 / Hα .

Fig. 3.— *Bottom:* Theoretical dependence of He I $\lambda5876$ / Hα on the hardness of the stellar continuum. The circles denote the line intensities of nebulae ionized by Kurucz model atmospheres (1979) with effective temperatures of 35,000 K, 40,000 K, 45,000 K, and 50,000 K (CLOUDY version 84.09, Ferland 1993). The clouds have O/H = $0.20(\mathrm{O/H})_\odot$; and the closed and open circles represent models with He/H abundance ratios of 0.08 and 0.09, respectively. The He I $\lambda5876$ / Hα ratios observed in the DIG are indicated. *Top:* The mass of a main sequence star producing an ionzing spectrum with a given hardness. The four mass scales were derived from: (a) the stellar evolution grid of Maeder (1990) at the Kurucz effective temperature and solar metallicity (0.25 $Z_\odot$ in parentheses). (b) the same T(M,Z) as in *a*, but the stellar atmospheres of Schaerer et al. (1996) which include wind effects and produce a harder ionizing spectrum at a given temperature, (c) the same stellar atmospheres as *b*, but using the evolutionary mass from Vacca et al. (1995) as interpolated from the grid of solar metallicity stellar evolution calculations by Schaller et al. (1992), and (d) for comparison, from equation 10 of Heiles et al. (1996) which relies on older atmospheric models.